Self-heated thermocouples for far-infrared detection

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A novel self-heated Bi-Sb thermocouple for far-infrared detection has been developed. The detector is suitable for integration with monolithic antennas and imaging arrays. The device is fabricated in a single photolithography masking step using a photoresist-bridge technique. This bridge technique has also been used to make microbolometers with lower $1/f$ noise than those made by two conventional masking steps. The thermocouples have a noise equivalent power (NEP) of 7×10^{-10} W/$\sqrt{Hz}$ and a 3-dB frequency response of 150 kHz.

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At 100–1000-μm wavelengths the choice of small size detectors suitable for integration into monolithic circuits such as focal-plane imaging arrays is quite limited. Above 300 GHz many semiconductor devices become difficult to make. Detectors that simply measure the temperature change caused by the absorption of far-infrared radiation have proven their great utility in many configurations: low-temperature bolometers, both self-absorbing[1] and coupled to passive absorbers;[2] room-temperature pyroelectrics,[3,4] and various thermocouples and thermopiles.[5,6] Especially useful as an antenna-coupled detector is the bismuth microbolometer.[7] This work describes a novel self-heated thermocouple that can be used interchangeably with the microbolometer. The advantage of the thermocouple is that it is not biased, and so has no $1/f$ noise. This makes the thermocouple more sensitive at low frequencies than the microbolometer.

Crucial in the fabrication of these detectors is the use of offset mask lift-off photolithography. First described by Dolan[8] and Dunkleburger,[9] it allows the suspension of a bridge of photoresist above the substrate. This technique has been used to prepare superconductor-insulator-superconductor tunnel junctions for use as mixers at 115 GHz.[10] In our process we use a plasma-formed buffer layer between the two resist layers.[11,12] A finished bridge structure is shown in Fig. 1, viewed at an 85° angle to the normal. By evaporating at oblique angles the material can be selectively deposited under the bridge from both sides (Fig. 2). For all our devices 100 nm of silver is first evaporated at normal incidence onto the glass substrate, forming low-frequency connections and also forming the bow-tie antenna used for coupling far-infrared radiation into the detector.[13] The width of the bridge is typically 3 μm, leaving a gap of the same size between the silver bows into which the detector materials are deposited. By evaporating 200 nm bismuth at an angle of approximately 45°, followed by 150 nm antimony at 50° from the normal, a bismuth-antimony thermocouple is formed between the silver tips (Fig. 3). Typical dc resistances for the thermocouples lay in the 50–100-Ω range.

The performance of the detectors can be easily evaluated by using a VHF signal (150 MHz) that is amplitude modulated to simulate the far-infrared amplitude-modulated radiation. The 150-MHz signal causes resistive heating in the detector just as the far-infrared does since both bismuth and antimony have such short scattering times[14] they behave resistively at both frequencies. The advantage of this approach is that the rf energy is efficiently coupled into the detector. The device responsivity is measured independently of the far-infrared coupling efficiency, which will vary from system to system. For these tests the silver bow-tie is bonded into an rf circuit that applies the 150-MHz signal through a high-

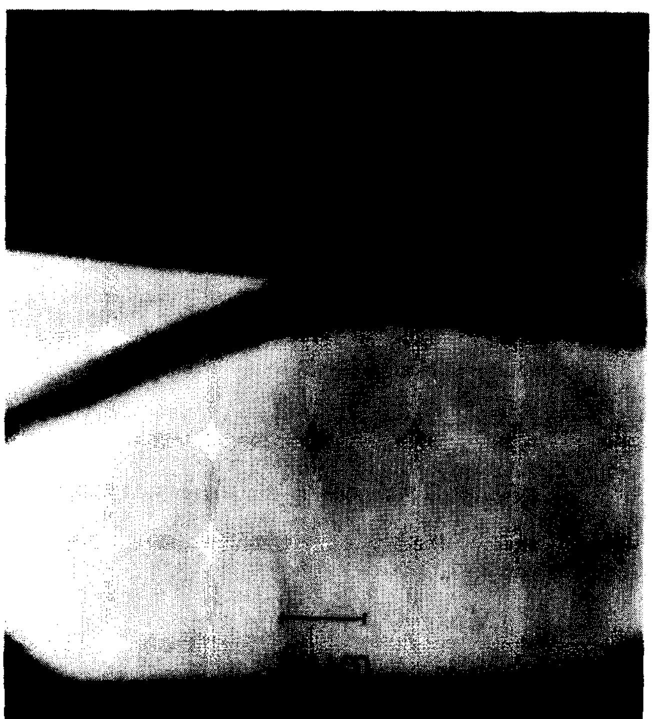

FIG. 1. Scanning electron micrograph of suspended-photoresist bridge. The bridge is about 2 μm above the substrate.

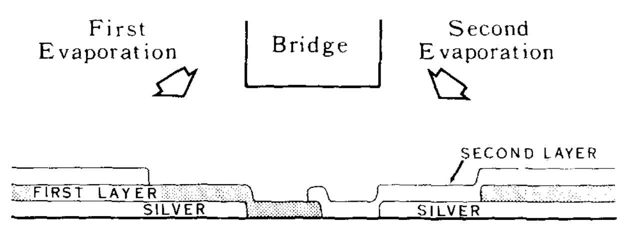

FIG. 2. Schematic of oblique evaporation process. The detector is formed in the gap between the two silver layers.

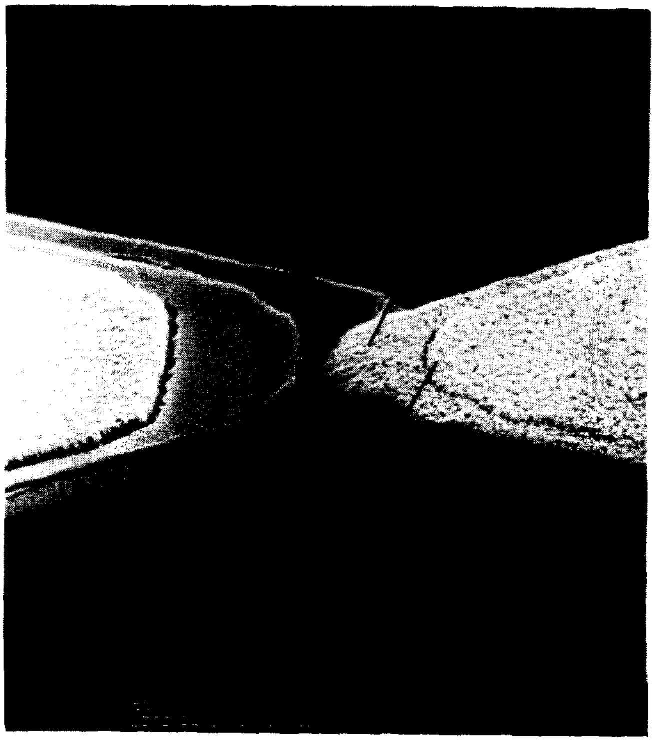

FIG. 3. Scanning electron micrograph of a bismuth-antimony self-heated thermocouple.

pass filter. It also allows measurement through a low-pass filter of the detector signal. The responsivity of the bismuth-antimony thermocouple versus modulation frequency is shown in Fig. 4. The frequency response is in qualitative agreement with the model of Hwang *et al.*,[7] which predicts that the responsivity rolls off when the substrate thermal diffusion length is equal to the device radius. In far-infrared measurements at 1.22 mm a typical output signal of 400 μV at 1.6-mW input power was obtained. The coupling efficiency of the optical system and the antenna is approximately 25% (determined from microwave modeling of the antenna array).[15] This yields a device responsivity of 1 V/W, in agreement with the 150-MHz result of 1.5 V/W.

The magnitude of this responsivity is somewhat surprising. As can be seen from Fig. 3, there is no true cold bismuth-antimony reference junction. Since the silver effectively shorts out any thermoelectric voltages outside the gap between the tips, the only temperature gradient available to generate voltages is that across the 3-μm gap. Assuming the tips of the silver are at roughly the same temperature, the couple measures the temperature difference between the bismuth-antimony junction and the silver tips. In order to determine the temperature rise the thermoelectric powers of thin-film bismuth and antimony must be known. It had been reported that the thermopower of antimony is independent of thickness, but that of bismuth decreases rapidly at thicknesses below 1 μm.[16] However, when we made a series of self-heated couples with bismuth thickness varying between 50 and 800 nm, no systematic variation in responsivity was found. Further measurements on large area, thin-film bismuth-antimony thermocouples in which a known temperature gradient could be established confirmed this observation. For bismuth thicknesses between 100 and 800 nm the thermoelectric power was independent of thickness, and consistent with the bulk value of $-73\ \mu$V/°C. The thermoelectric coefficient for the couples was also consistent with the bulk value of 120 μV/°C. Using this value, the

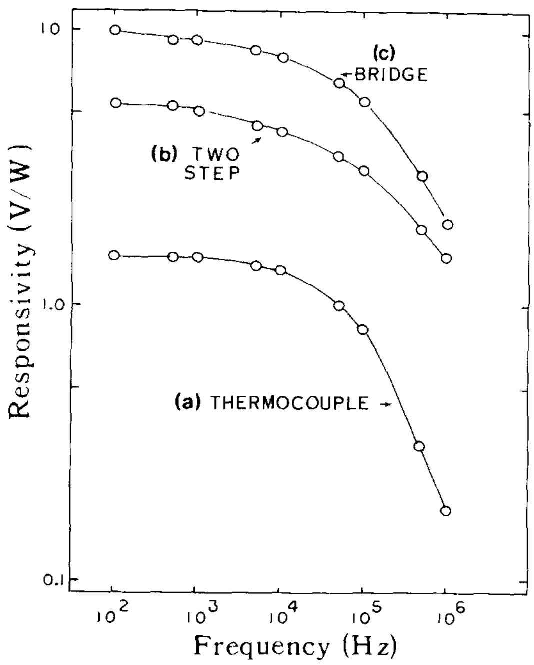

FIG. 4. Responsivity of various detectors; the bolometers are biased at the largest practical voltage. (a) Bi-Sb self-heated thermocouple, no bias; (b) conventional two-step microbolometer, 0.23-V bias voltage; (c) oblique evaporated microbolometer using photoresist bridge as a mask, 0.23-V bias voltage.

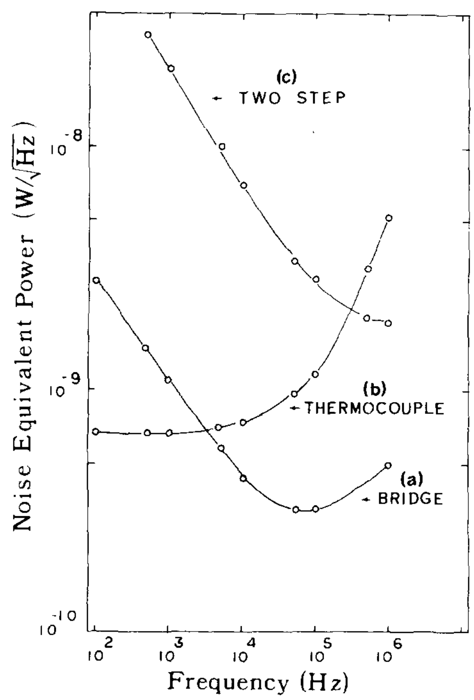

FIG. 5. Noise equivalent power of the three detectors, same bias conditions as Fig. 4.

temperature difference (inferred from the responsivity measurements) between the silver tip and the bismuth-antimony junction 1.5 μm away is 12 °C per milliwatt of input power.

For comparison a bismuth microbolometer has also been fabricated using offset lithography. Here the first and second layers (see Fig. 2) are both 200-nm-thick bismuth. Typical responsivities of this bolometer and a standard two-step fabricated bolometer are shown in Fig. 4, and their noise equivalent power (NEP) is shown in Fig. 5. The noise was measured with a PAR-124 lock-in amplifier. The low-frequency NEP of both bolometers is dominated by $1/f$ noise. The bridge fabricated detector has a much smaller $1/f$ noise than the standard bolometer. Note that the single-step offset mask allows the deposition of the bismuth on a fresh silver surface. In the standard two-step lift-off process, the silver would be defined first, followed by a second photoresist layer to define the bismuth pattern. It is possible that the excess $1/f$ noise is due to poor surface contact between the silver and bismuth, induced by surface contamination from the lithographic process.

Since the bismuth-antimony thermocouple is an unbiased detector, it is free from $1/f$ noise; its NEP is limited by Johnson noise. Figure 5 shows that for modulation frequencies below 3 kHz the thermocouple has a better NEP than either bolometer. In this frequency range, even though the responsivity is smaller than that of the bolometers, the absence of $1/f$ noise allows the detection of a smaller signal. Above 3 kHz, the bridge-fabricated bolometer has a better NEP. For these frequencies the $1/f$ noise of the bolometer has fallen, and because of its large responsivity, provides more sensitive detection than the thermocouple.

In conclusion, we have developed a new self-heated thermocouple for use as a detector throughout the far-infrared. The device is relatively easy to fabricate, and is suitable for monolithic integration. It has an NEP of better than 10^{-9} W/$\sqrt{\text{Hz}}$ for modulation frequencies from dc to 50 kHz. Optimization of the device geometry should increase its sensitivity further.

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